SUMMIT CARBON
SOLUTIONS

February 23, 2023

HAND DELIVERED TO:
Burleigh County Commission
c/o Leo Vetter Auditor/Treasurer
221 North 5th Street
P.O. Box 5518
Bismarck, ND 58506-5518

RE: Proposed Burleigh County Public Health Statement
[1-30-2023]

Dear Burleigh County Commissioners:

We have reviewed the proposed Burleigh County Public Health Statement dated 1-30-2023. Pipelines are the safest mode of transportation of gases and liquids, and CO_2 lines rank high in safety due in large part to the existing regulations. In fact, The International Journal of Greenhouse Gas Control, Volume 116, dated May 2022, published *CO_2 Pipeline risk assessment and comparison for the midcontinent United States*, which was funded by the United State Department of Energy. The paper was a collaborative effort with multiple authors with "no known competing financial interest or personal relationship that could have appeared to influence the work." The conclusion that was drawn is that the "**Risks associated with CO2 pipelines are significantly less than those of other pipeline types**."[1] A full copy of this report is attached and was hand delivered to Leo Vetter. Additional copies are available upon request.

Sincerely,

Jeffrey L. Skaare, J.D., C.P.L.
Summit Carbon Solutions, LLC

W108
PU-22-391

[1] See Summary of authored work - https://www.sciencedirect.com/science/article/abs/pii/S175058362200055X

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CO_2 Pipeline risk assessment and comparison for the midcontinent United States

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ABSTRACT

A comprehensive quantitative risk assessment for the construction and operation of CO_2 transportation networks considered for the Midcontinent United States was conducted. The results showed risks associated with CO_2 pipelines were significantly less than those of other pipeline types. The assessment used four conceptual pipelines of different lengths to discuss risks operators may see. The assessment evaluated the risk associated with construction and operation using data from the US Occupational Safety Health Administration to determine the risk of injury or death for pipeline workers and data from the US Pipeline and Hazardous Materials Safety Administration for CO_2, natural gas distribution, natural gas transmission/gathering, and non-CO_2 hazardous liquid pipelines to develop quantitative likelihood and severity values leading to risk values. The data for the assessment covered incidents from 2010 to 2017 for CO_2 pipelines. The average risk for construction and 30 years of operation for four CO_2 pipeline configurations ranging between 79 and 1,546 miles in length was found. The construction and operational risk averaged between $1,400,521 (approximately $0.02/tonne of CO_2) for the shorter pipeline (79 miles) and $27,481,939 (approximately $0.10/tonne of CO_2) for a longer pipeline (1,546 miles). The largest risks of fatality for CO_2 pipelines comes from vehicle transport. The largest operational risk to the pipeline was due to leakage. Public pipeline opposition is also a significant risk; it was not quantified but is addressed.

1. Introduction

The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Program is phased to support the development of commercial-scale (50 million metric tonnes over a 30-year period) carbon capture, utilization, and storage (CCUS) in the United States. The Integrated Midcontinent Stacked Carbon Storage Hub (IMSCS-HUB) was funded during the first two phases of the program. The source corridor for the project contains ethanol plants and electric utilities in Iowa, Nebraska, and Kansas. The conceptual model for the project was to transport CO_2 by pipeline from the source corridor to sinks in a storage corridor in southwestern Nebraska and western Kansas (Fig. 1).

An assessment of CO_2 pipeline risk was conducted to estimate the risk posed by CO_2 pipelines. The risks calculated were then potential midcontinent pipelines as examples. The objective of the study was to calculate the economic value of the risk posed by CO_2 transport pipelines. The assessment involved (1) a review of past incidents (for gas transmission and distribution pipelines) and accidents (for CO_2 and other hazardous liquid pipelines) using data from 2010 to 2019; (2) a comparison of CO_2 pipeline accidents to accidents and incidents of other pipeline types; (3) development of the likelihood of occurrence values for features, events, and processes (FEPs) in the databases used; and (4) development of the severity of impact values for FEPs in the databases. The assessment allowed comparison between the expected risk of CO_2 pipelines and the risk of other types of pipelines if they followed the same routes.

This study considers pipeline four scenarios that connect ethanol plants in Nebraska and two power plants in Nebraska and Kansas to stacked storage areas in southwestern Nebraska (Sleepy Hollow Field) and western Kansas (Patterson Heinitz Hartland Field). The configurations ranged in length from 79 to 1546 miles. The longest pipeline scenario assumed CO2 was transported to Texas for CO_2-enhanced oil recovery This paper presents an investigation of the likelihood of occurrence, severity of impact, and causes of safety incidents for CO_2 pipelines.

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2. Background

Safely operating pipelines is important for CCUS projects. Current literature using pipeline operation and construction data suggests operating a natural gas or hazardous liquid pipeline is riskier than operating a CO_2 pipeline (Gale and Davison, 2004; Noothout et al., 2014; Han et al., 2015; Lueng et al., 2014)' however, many of these sources caveat these results with the small sample size. Two factors must be considered when reviewing pipeline safety issues: incident rate (likelihood) and incident severity. Lueng et al. (2014) found that the rate of incidents increased from the period 1990–2001 (0.30 incident/-year/621 miles) to and the period 2002–2008 (0.72 incident/year/621 miles), coinciding with an increase in the total length of the pipeline network from 1740 miles to 3602 miles. Gale and Davison (Gale and Davison, 2004) found that although there is evidence to suggest the rate of safety incidents associated with CO_2 pipelines is lower than that associated with hazard liquid pipelines, it could be expected to be equivalent to that of natural gas pipelines.

Between 1972 and 2012, there were 46 safety incidents involving CO_2 pipelines that were due to relief valve failure, weld/gasket/valve packing failure, corrosion, and outside force (Gale and Davison, 2004; Noothout et al., 2014; Lueng et al., 2014). Other potential causes of safety incidents include interval corrosion of pipelines due to contamination in the CO_2 stream, particularly water, which can mix with CO_2 and create carbonic acid, as well as human/operator error (Gale and Davison, 2004). In general, reported CO_2 safety incidents have been relatively minor compared with natural gas or hazardous liquid pipeline incidents. Gale and Davison (Gale and Davison, 2004) state that incidents involving CO_2 were less severe than those involving either hazardous liquid or natural gas pipelines, causing less than half and less than 10% of the property damage (in US dollars) per 621 miles of pipeline compared natural gas and hazardous liquid pipelines, respectively. In addition, between 1986 and 2001 safety incidents for CO_2 pipelines resulted in no fatalities or injuries compared with 58 fatalities (0.008 fatality/621 miles) and 217 injuries (0.029 injury/621 miles) for natural gas pipelines and 36 fatalities (0.01 fatality/621 miles) and 249 injuries (0.067 injury/621 miles) for hazardous liquid pipelines.

Koornneefa et al. (2009) investigated uncertainties of quantitative risk assessments and conducted a sensitivity analysis to determine the impacts uncertainties have on risk models. This study used release, dispersion, and impact models to quantify CO_2 release, and conducted literature reviews to determine the influencing parameters.

Trabucchi et al., (2014) used a model developed by IEc and applied it to a site-specific CCS project to estimate possible future economic damages. The pipeline events parameter considered two possible scenarios: a hole puncture and a complete severing of the pipeline. They estimated a 78% chance that there would be no damage in the case of a rupture, while at the 95th percentile, the damage estimate was $314, 000. They estimated a 61% chance there would be no damages from a pipeline puncture, while at the 95th percentile, the damage estimate was $215,000. This study concludes that these potential damages are low due to the rural setting, which limits the potential for adverse effects to human health and habitats.

Duncan et al. (2009) used available data on the operational track record from CO_2-EOR-related transportation and injection to assess associated health and safety risks. Case studies were developed for two

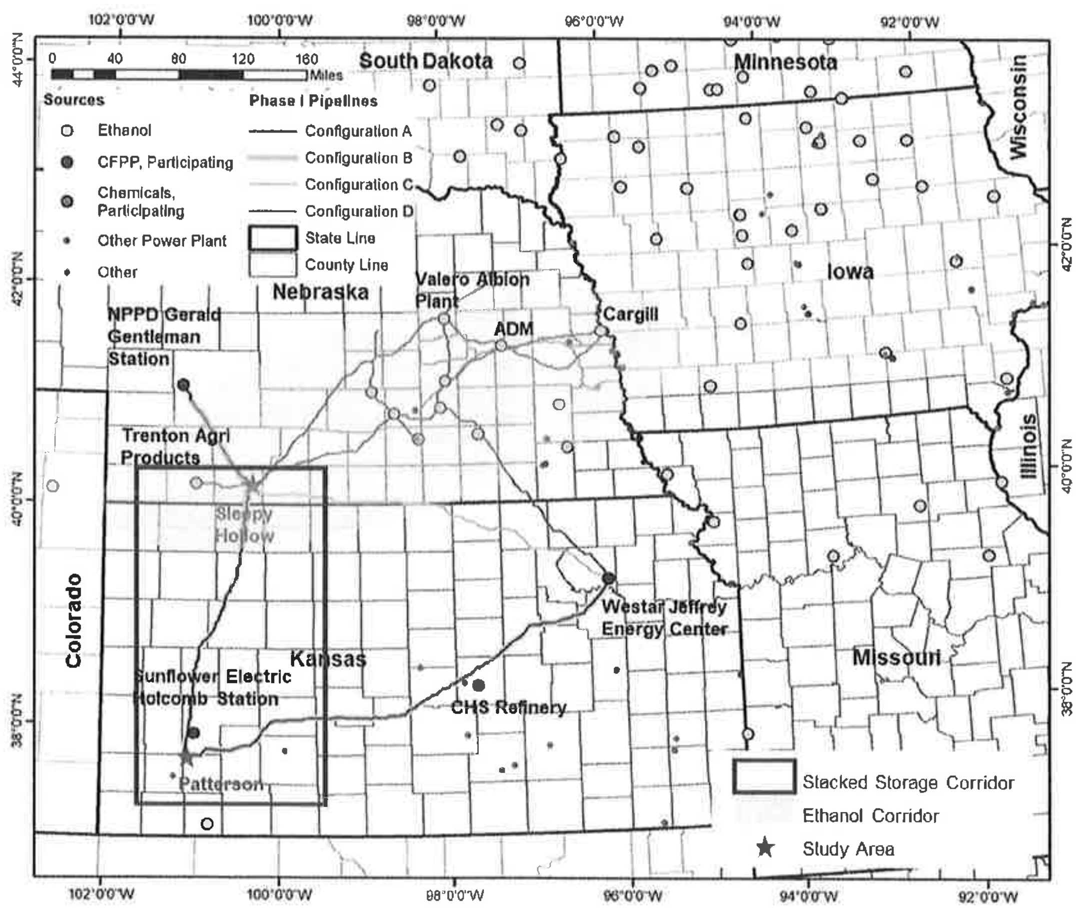

Fig. 1. Conceptual model for the IMSCS-HUB Project.

pipeline complexes. The first case study documents a 204-mile pipeline with a 5-Mt/year capacity. Since operation began in 2000, there has only been one minor leak due to a part failure. The second case study documents a cross-country pipeline. This study had five accidental releases. The releases were caused by manufacturing errors, outside force by a third party, and human error.

This study uses similar approaches as those described to estimate both the likelihood of occurrence and severity of impact for pipeline-related risks. The assessment developed the risk in dollars to allow potential CCUS projects to understand their risk exposure in a manner that can be compared with their project income or project costs or allow for the purchase of proper insurance. Data from the Bureau of Labor Statistics (BLS) were used to determine the likelihood of injuries or fatalities during pipeline construction and operation per mile of pipeline. Severity of impact for the injuries was assigned a dollar value based on costs associated with hospitalization, lost wages, and potential litigation. Severity for pipeline operations is valued using data from PHMSA (Pipeline and Hazardous Materials Safety Administration 2019). The calculated risk for pipeline construction and operations is applied to the four pipeline routes shown in Fig. 1.

3. Methods

Detailed reports are submitted by pipeline operators for all incidents and accidents, and PHMSA releases data by pipeline system type and by year. A review of accidents/incidents for pipeline operations was conducted using PHMSA (Pipeline and Hazardous Materials Safety Administration 2019) data from 2010 to 2017 for CO_2 pipelines, natural gas distribution pipelines, natural gas transmission/gathering pipelines, and non-CO_2 hazardous liquid pipelines. Data and accident reports for CO_2 pipelines are released within the hazardous liquid pipeline dataset, so all CO_2 data were separated by the "commodity-type" parameter and treated independently. Hazardous liquid data presented in this report do not include CO_2 data.

The data were used to determine the risk posed by CO_2 pipeline operations and compare the risk to that posed by other types of pipelines. PHMSA maintains a quantitative database with annual reports on gas distribution pipelines, hazardous liquids pipelines, and gas transmission and gathering pipelines, as well as data on underground natural gas storage and liquefied natural gas (LNG) facilities. Pipeline mileage and facilities reports include the number of pipeline miles organized by different features such as location, material type, strength, diameter, decade installed, and inspection method, as well as specifications on the pipeline system type and commodity transported. The data in this paper are aggregated and do not consider specific operating conditions. PHMSA also releases annual data on incidents and accidents for each type of pipeline system (Pipeline and Hazardous Materials Safety Administration 2019). Current regulations [49 CFR 191.3, 2016] define an "incident" as any of the following events:

1 An event that involves a release of gas from a pipeline, or of liquefied natural gas, liquefied petroleum gas, refrigerant gas, or gas from an LNG facility, and that results in one or more of the following consequences:
   a A death, or personal injury necessitating inpatient hospitalization
   b Estimated property damage of $50,000 or more, including loss to the operator and others, or both, but excluding cost of gas lost
   c Unintentional estimated gas loss of 3 million cubic feet or more
2 An event that results in an emergency shutdown of an LNG facility. Activation of an emergency shutdown system for reasons other than an actual emergency does not constitute an incident.
3 An event that is significant in the judgment of the operator, even though it did not meet the criteria of paragraphs (1) or (2) of this definition.

Incidents are specific to gas distribution pipelines, gas transmission pipelines, and LNG facilities. Events that regulations consider similar in magnitude for hazardous liquid pipelines are referred to as "accidents." Current regulations [49 CFR 195.50, 2002] define an "accident" as a release of the hazardous liquid or carbon dioxide transported resulting in any of the following:

1 Explosion or fire not intentionally set by the operator
2 Release of 5 gallons (19 liters) or more of hazardous liquid or carbon dioxide, except that no report is required for a release of less than 5 barrels (0.8 m^3) resulting from a pipeline maintenance activity if the release is:
   a Not otherwise reportable under this section
   b Not resulting in pollution of any stream, river, lake, reservoir, or other similar body of water that violated applicable water quality standards, caused a discoloration of the surface of the water or adjoining shoreline, or deposited a sludge or emulsion beneath the surface of the water or upon adjoining shorelines (described in §195.52[a][4])
   c Confined to company property or pipeline right-of-way; and
   d Cleaned up promptly
3 Death of any person
4 Personal injury necessitating hospitalization
5 Estimated property damage, including cost of clean-up and recovery, value of lost product, and damage to the property of the operator or others, or both, exceeding $50,000

In an event of pipeline failure, the severity of impact to surrounding lands varies with environmental and socioeconomic sensitivity of the area. The routes were chosen considering a regional analysis of wetlands, wildlife and protected species, water resources, publicly owned lands, historic places, schools, parks, high population densities, and other features that may impact risk. The selection criteria for the pipeline route are described in Bacon et al. (2018); however, only their lengths are important for this analysis. Risk was assessed for four potential pipeline routes identified in the first phase of the project (Fig. 1). Configuration A consisted of 344 miles of pipeline; Configuration B, 295 miles of pipeline; Configuration C, 79 miles of pipeline; and Configuration D, 1546 miles of pipeline. The likelihood of a risk was determined quantitatively using past occurrence with data from the databases detailed below. The severity of the risk was estimated by determining the overall monetary value of the outcome. For fatalities, this meant placing a value on the loss of a human life. For injuries, this involved placing a value on hospital stays, time away from work, and potential litigation. For pipeline accidents, this included using the costs of previous accidents reported by PHMSA (Pipeline and Hazardous Materials Safety Administration 2019). Risk was then determined by multiplying the likelihood of occurrence by the severity of impact in dollars (Eq. (1)).

$$\text{Risk} = \text{likelihood} * \text{severity} \tag{1}$$

Risks for pipeline construction and operation workers were assessed using data from BLS. BLS provides data on fatal injuries by event or exposure, as well as nonfatal injury, illness, and incident data by industry; these represent FEPs for this assessment. Data for two industries, oil and gas pipeline and related structures construction and pipeline transportation, were gathered for this risk assessment. The data were used to inform the likelihood and severity of pipeline construction and operation risks.

The types, consequences, and costs of incidents and accidents were used to assess CO_2 pipeline incident rates and compare them to incident rates of other pipeline systems. Data about the release type, the release cause, and the identifier were quantified for each system. Numbers of fatalities, injuries, evacuations, fires, and environmental contamination were also gathered to analyze the likelihood of occurrence and the severity of the consequences. PHMSA provides detailed cost breakdowns for each release by reporting the costs for property damage, non-operator property damage, emergency response, environmental remediation, and lost commodity. Pipeline material and decade installed were noted for each release to study possible correlations between pipeline features and incident rates.

4. Results

4.1. Past pipeline accidents/incidents (2010–2017)

Pipeline incidents and accidents were split into four categories:

- *Area/system:* Release accident location
- *Accident type:* Release type, cause, and identifier
- *Pipeline specifications:* Pipeline installation year and material
- *Accident consequences:* Fatalities, injuries, evacuations, ignitions, explosions, and environmental impact resulting from the release accident, and minimum, maximum, and average costs of operator and non-operator property damage, emergency response, environmental damage, gas released, other, and total cost of accident

The raw incident and accident data are presented in the Supplemental Data Table 1 in the supplemental data file for this paper.

4.1.1. Total accidents

There were 53 accidents involving CO_2 pipelines between 2010 and 2017, compared to 974, 1113, and 3603 accidents reported for gas distribution, gas transmission, and non-CO_2 hazardous liquid pipelines, respectively (Pipeline and Hazardous Materials Safety Administration 2019).

4.1.2. Pipeline specifications

Although most pipelines are underground pipelines, nearly two-thirds of CO_2 pipeline accidents occurred at sections of pipeline that are above ground. Non-CO_2 hazardous liquid pipelines also had a slight majority (53%) of accidents occurring at aboveground sections of pipeline, with an additional 12% of accidents occurring at transition zones or in storage tanks. Gas distribution and transmission pipelines had more accidents occurring below ground than above ground, but 40% and 41%, respectively, of accidents in these pipelines occurred above ground.

Pipeline age was examined to investigate if accidents were more prevalent for older pipelines. Forty-three of the accidents (81% of all accidents) reported the age of the pipeline. Accidents at CO_2 pipelines skewed toward newer pipelines; 14 accidents occurred in pipelines installed before 2010, while 29 of the accidents were in pipelines installed between 2010 and 2017. Pipeline age for accidents at non-CO_2 hazardous liquid pipelines also skewed toward newer pipelines: only 19% of the pipelines with accidents were constructed prior to 1970, whereas 21% of accidents occurred in pipelines constructed in 2010 or later. (*Note:* 38% of the reported accidents did not provide the age of the pipeline.) Pipeline ages for accidents in gas distribution and gas transmission were more evenly distributed—only 9% and 10% of accidents in pipelines constructed in 2010 or later for gas distribution pipelines and gas transmission pipelines, respectively. Each decade from 1950 to 2017 had between 7% and 15% of accidents in gas distribution pipelines and

Table 1
Average likelihood (x 10,000 FTE) and risk for injuries requiring hospitalization for pipeline Configurations A through D.

Event/Exposure		Intentional injury/ violence	Transportation Incidents	Fire and explosions	Slips, trips, falls	Exposure to harmful substances, environments	Contact with objects, equipment	Overexertion, body reaction	Cause not indicated	TOTAL
Likelihood Avg (per 10,000 FTE)		0.186	3.2	0.486	8.586	0.443	15.014	7.043	1.643	36.643
Event Severity ($)		$226,538	$226,538	$226,538	$186,538	$186,538	$186,538	$186,538	$186,538	NA
Configuration A Likelihood	**Min**	0.044	0.751	0.114	2.016	0.104	3.525	1.653	0.386	8.603
	Avg	0.061	1.044	0.159	2.801	0.145	4.897	2.297	0.536	11.953
	Max	0.086	1.473	0.224	3.952	0.204	6.91	3.241	0.756	16.864
Configuration A Risk ($)	**Min**	$9968	$170,130	$25,825	$376,061	$19,400	$657,546	$308,347	$72,004	$1639,281
	Avg	$13,819	$236,506	$36,020	$522,493	$27,048	$913,477	$428,478	$99,984	$2277,824
	Max	$19,482	$333,690	$50,745	$737,198	$38,054	$1288,978	$604,570	$141,023	$3213,739
Configuration B Likelihood	**Min**	0.037	0.644	0.098	1.729	0.089	3.023	1.418	0.331	7.377
	Avg	0.052	0.895	0.136	2.402	0.124	4.2	1.97	0.46	10.25
	Max	0.073	1.263	0.192	3.389	0.175	5.926	2.78	0.648	14.462
Configuration B Risk ($)	**Min**	$8382	$145,890	$22,201	$322,524	$16,602	$563,904	$264,511	$61,744	$1405,759
	Avg	$11,780	$202,752	$30,809	$448,064	$23,131	$783,460	$367,480	$85,807	$1953,283
	Max	$16,537	$286,117	$43,495	$632,177	$32,644	$1105,424	$518,576	$120,877	$2755,848
Configuration C Likelihood	**Min**	0.01	0.173	0.026	0.463	0.024	0.809	0.38	0.089	1.976
	Avg	0.014	0.24	0.036	0.643	0.033	1.125	0.528	0.123	2.745
	Max	0.02	0.338	0.051	0.907	0.047	1.587	0.744	0.174	3.873
Configuration C Risk ($)	**Min**	$2265	$39,191	$5890	$86,367	$4477	$150,909	$70,884	$16,602	$376,586
	Avg	$3172	$54,369	$8155	$119,944	$6156	$209,855	$98,492	$22,944	$523,087
	Max	$4531	$76,570	$11,553	$169,190	$8767	$296,036	$138,784	$32,458	$737,889
Configuration D Likelihood	**Min**	0.196	3.376	0.513	9.059	0.467	15.841	7.431	1.734	38.662
	Avg	0.273	4.691	0.712	12.587	0.649	22.01	10.325	2.409	53.717
	Max	0.385	6.619	1.005	17.759	0.916	31.055	14.568	3.398	75.792
Configuration D Risk ($)	**Min**	$44,401	$764,792	$116,214	$1689,848	$87,113	$2954,948	$1386,164	$323,457	$7366,938
	Avg	$61,845	$1062,690	$161,295	$2347,954	$121,063	$4105,701	$1926,005	$449,370	$10,235,923
	Max	$87,217	$1499,455	$227,671	$3312,728	$170,869	$5792,938	$2717,486	$633,856	$14,442,219

Notes: The minimum, average, and maximum number of FTEs (i.e., 40 h a week, 50 weeks a year, or 2000 h) needed for each pipeline route was based on the minimum, average, and maximum values for the miles of pipeline constructed per FTE: 0.0747 mile/FTE, 0.105 mile/FTE, and 0.147 mile/FTE, respectively. The lowest (minimum) number of miles built per FTE translates to the highest number of FTE needed and, thus, the highest (maximum) likelihood of an event/exposure. The severity of these events is calculated based on the cost of lost wages from the average of the median days off work (22.3 days; $6728.41 based on US Census (PHMSA 2017)), the cost of the hospital stay of $10,000 a day, (Department of Health and Human Services (nd)) and $150,000 in litigation (estimate) and other expenses per injury. Estimated hospital stays varied from three days—for slips, trips, and falls; exposure to harmful substances or environments; contact with objects, equipment; overexertion, body reaction; and cause not indicated—to 7 days—for intentional injury/violence; transportation incidents; and fire and explosions. Risk = likelihood x severity. Configuration A: Number of workers, FTW-equivalent (x 10,000): Min – 0.235 | Avg – 0.326 | Max – 0.460. Configuration B: Number of workers, FTW-equivalent (x 10,000): Min – 0.201 | Avg – 0.280 | Max – 0.395. Configuration C: Number of workers, FTW-equivalent (x 10,000): Min – 0.054 | Avg – 0.075 | Max – 0.106. Configuration D: *Number of workers, FTW-equivalent (x 10,000): Min – 1.055 | Avg – 1.466 | Max – 2.068* gas transmission pipelines. Pipelines constructed prior to 1950 accounted for 7% of accidents in gas distribution pipelines and 10% of accidents in gas transmission pipelines.

Most CO_2 pipeline accidents (more than 80%) occurred in steel pipelines, with the remaining occurring in pipelines of other (nonplastic) materials or of material that was not indicated. While most accidents in non-CO_2 hazardous liquid pipelines occurred in pipelines made of steel (64%), steel pipelines represented a significantly lower proportion of reported accidents versus pipelines of other or unknown materials. Like CO_2 pipelines, none of the reported accidents for non-CO_2 hazardous liquid pipelines were for pipelines made of plastic.

A plurality (45%) of accidents in gas distribution pipelines occurred in steel pipelines; however, nearly a third of the accidents occurred in plastic pipelines. The remaining accidents occurred in pipelines of other materials (21%) or pipelines where the material was not indicated (3%). In contrast, nearly all accidents in gas transmission pipelines (94%) were in steel pipelines while less than 1% occurred in plastic pipelines, and the remaining accidents did not indicate the pipeline material.

4.1.3. Accident type

Forty-six of 53 CO_2 pipeline accidents were leaks, with two accidents related to ruptures, one mechanical puncture, and four miscellaneously classified accidents. These proportions are similar to non-CO_2 hazardous liquid pipeline leaks, where 78% of accidents (2817 of 3603 accidents) were pipeline leaks, with most of the remaining miscellaneously classified (606 accidents). Only 5% of accidents for non-CO_2 hazardous liquid pipelines were mechanical punctures (121 accidents) or ruptures (89 accidents).

Gas distribution and transmission pipeline release types were more variable. Roughly equal percentages of accidents for gas distribution and gas transmission pipelines were classified as leaks and mechanical punctures, accounting for 67% (654 of 974 accidents) and 76% (856 of 1113 accidents) of accidents at these pipelines, respectively. Ruptures accounted for 13% of the accidents for gas transmission pipelines (147 of 1113 accidents) but only 5% of the accidents for gas distribution pipelines (46 of 974 accidents). The remaining 28% of accidents for gas distribution pipelines (274 of 974 accidents) and 11% of accidents for gas transmission pipelines (110 of 1113 accidents) were miscellaneously classified release types.

Forty-two of the 53 reported accidents at CO_2 pipelines (79% of accidents) were caused by corrosion and material failure or equipment failure. Incorrect operation was the cause for 13% of accidents at CO_2 pipelines (seven of 53 accidents); one accident was caused by outside force, and the remaining three accidents were attributed to miscellaneously classified causes. No CO_2 pipeline accidents were caused by excavation. Similar proportions of accident causes were found at non-CO_2 hazardous liquid pipelines, where 27% of accidents were caused by corrosion and material failure (985 of 3603 accidents), 46% of accidents were caused by equipment failure (1648 of 3603 accidents), and 14% of accidents were caused by incorrect operation (516 of 3603 accidents). The remaining accidents at non-CO_2 hazardous liquid pipelines were caused by incorrect operation (7%), excavation (4%), or miscellaneously classified causes (3%).

Gas distribution pipeline accidents were caused largely by outside force or excavation (390 and 290 of 974 reported accidents, respectively, 70% of accidents). The remaining accidents were caused by corrosion and material failure (9%), equipment failure (5%), incorrect operation (7%), or miscellaneously classified causes (9%). Causes of accidents at gas transmission pipelines were different, with nearly two-thirds of accidents caused by corrosion and material failure (31%) or equipment failure (31%). Excavation and outside force were the causes of a little more than a quarter of the accidents. Other accidents at gas transmission pipelines were caused by incorrect operation (6%) and miscellaneously classified causes (5%).

Thirty of the 53 accidents at CO_2 pipelines (57%) were identified by pipeline workers or other professionals. The general public or third parties reported 11 of the 53 accidents at CO_2 pipelines (21%). Computerized monitoring, such as computational pipeline monitoring (CPM) or Supervisory Control and Data Acquisition (SCADA) systems, identified four of the 53 accidents (7%). Additional accidents at CO_2 pipelines were identified by miscellaneously classified identifiers (6%), or no identifier was indicated (9%). Accident identifiers were similar for non-CO_2 hazardous liquid pipelines and gas transmission pipelines. Pipeline workers, other professionals, and third parties and the general public identified most of the incidents/accidents. Computerized monitoring and miscellaneously classified identifiers made up, respectively, 7% and 5% of reported accidents. An additional 20% of these accidents did not have the accident identifier indicated.

Computerized monitoring and miscellaneously classified identifiers reported a higher proportion of accidents at gas transmission pipelines (15% and 13%, respectively) compared to CO_2 pipelines or non-CO_2 hazardous liquid pipelines. Accident identifiers at gas distribution pipelines were nearly all people, with nearly seven in ten accidents identified by pipeline workers or other professionals and an additional quarter of the accidents identified by third parties and the general public. The remaining accidents were identified by computerized monitoring (2%) or miscellaneously classified identifiers (4%).

4.1.4. Nonmonetary accident consequences

Consequences of accidents at CO_2 pipelines were limited, particularly when compared to the accidents reported for natural gas distribution, natural gas transmission, and non-CO_2 hazardous liquid pipelines. None of the 53 accidents reported for CO_2 pipelines resulted in injuries, fatalities, or public evacuations. In contrast, accidents at non-CO_2 hazardous liquid pipelines had the following consequences:

- A total of nine people were killed in seven accidents with at least one fatality (0.2% of all reported accidents).
- A total of 27 people were hospitalized in 11 accidents with at least one injury requiring hospitalization (0.3% of all accidents).
- A total of 64 accidents (1.8% of all accidents) required evacuations.
- The released product was ignited in 97 accidents (2.7% of all accidents).
- There was an explosion in 12 accidents (0.3% of all accidents).

Nonmonetary consequences of gas distribution pipelines were the most severe of all the pipeline types analyzed:

- A total of 95 people were killed in 59 accidents with at least one fatality (6.1% of all reported accidents).
- A total of 587 people were hospitalized in 221 accidents with at least one injury requiring hospitalization (22.7% of all accidents).
- A total of 428 accidents (43.9% of all accidents) required evacuations.
- The released gas was ignited in 595 accidents (61.1% of all accidents).
- There was an explosion in 235 accidents (24.1% of all accidents).

Nonmonetary consequences of gas transmission pipelines were also severe compared to non-CO_2 hazardous liquid pipelines:

- A total of 24 people were killed in 12 accidents with at least one fatality (0.7% of all reported accidents).
- A total of 103 people were hospitalized in 23 accidents with at least one injury requiring hospitalization (2.1% of all accidents).
- A total of 112 accidents (10.1% of all accidents) required evacuations.
- The released product was ignited in 127 accidents (11.4% of all accidents).
- There was an explosion in 54 accidents (4.9% of all accidents).

Hazardous liquid pipeline regulations require reporting of applicable environmental impacts caused by pipeline accidents. No accidents from CO_2 pipelines impacted wildlife, soil contamination, or water. None of the releases led to long-term assessments. One of the releases (1.9% of all accidents) required remediation of affected vegetation; however, remedial costs were relatively minor. In contrast, non-CO_2 hazardous liquid pipelines had 261 accidents requiring a long-term environmental assessment (7.2% of all accidents), 1062 accidents requiring environmental remediation (29.5% of all accidents), 2060 accidents resulting in soil contamination (57.2% of all accidents), 316 accidents resulting in groundwater contamination (8.8% of all accidents), and 56 accidents that impacted wildlife (1.5% of all accidents).

4.1.5. *Monetary consequences*

Financial costs were incurred in each of the 53 CO_2 pipeline accidents reported in the PHMSA database. The raw monetary consequence data are presented in Supplemental Data Table 2. The total costs of these accidents varied by five orders of magnitude from $2 (cost of the gas released) to $205,645, with an average value of $23,808. Detailed costs presented in the PHMSA database are summarized: Financial costs were incurred in 955 of the 974 gas distribution pipeline incidents. The total costs of these incidents varied by seven orders of magnitude from $5 to $734,000,000 (average of $1184,869, median of $88,746). Detailed costs presented in the PHMSA database are summarized below: Financial costs were incurred in 1107 of the 1113 gas transmission pipeline incidents. The total costs of these incidents varied by five orders of magnitude from $500 to $558,363,000, with an average of $1021,652 and median of $124,000. Financial costs were incurred in 3578 of the 3603 non-CO_2 hazardous liquid pipeline accidents. The total costs of these accidents varied by nearly eight orders of magnitude from $1 to $840,526,118, with an average of $748,473 and median of $25,155.

Figs. 2 displays, respectively, the minimum, average, and maximum costs for each pipeline system. Minimum costs were variable between the pipeline systems. All systems had at least some significant costs associated with emergency response, environmental remediation, and "other." Average costs were lowest for CO_2 pipelines in almost all types of costs, except the average cost of commodity released was lowest in gas distribution pipelines. All average costs for the other pipeline systems seemed to be relatively comparable. Maximum costs were also lowest for CO_2 pipelines for almost all cost types, but had comparable maximum commodity released costs with gas distribution pipelines. For gas distribution and gas transmission pipelines, both categories of property damage and "other" had the highest costs, while hazardous liquids were the most expensive for costs relating to environmental damage and emergency response Fig. 2. also presents the number of accidents associated with each cost category for each type of pipeline. CO_2 pipelines had the fewest accidents associated with each type of cost, although accidents associated with environmental costs were comparable to gas distribution pipelines. Non-CO_2 hazardous liquids pipelines had more accidents associated with each type of cost except for costs associated with non-operator property damage.

4.2. *Normalized comparisons of CO_2 pipeline accidents to other pipeline types*

The number of accidents and consequences of the accidents for each pipeline are divided by the miles of pipeline in the US (supplemental data) to create a normalized view of the potential risk of each pipeline type. The number of accidents per mile of pipeline is highest for non-CO_2 hazardous liquid pipeline, followed by CO_2 pipelines, gas transmission, and gas distribution pipelines.

The consequences of accidents were greater for hazardous non-CO_2, gas distribution, and gas transmission pipelines compared to CO_2 pipelines. CO_2 pipelines did not have any accidents with fatalities, injuries requiring hospitalization, evacuations, ignitions (CO_2 is not flammable), or explosions for the period 2010–2017. Natural gas distribution pipelines, natural gas transmission pipelines, and non-CO_2 hazardous liquid pipelines each had accidents with each of these consequences.

Forty three percent of CO_2 pipelines were constructed in the 1980s. The miles of pipeline by decade installed compared to the number of accidents for each type of system are presented in Supplemental Data

Table 2
Average likelihood (x 10,000 FTE) and risk for fatalities for pipeline Configurations A through D, by event/exposure.

Event/Exposure		Intentional injury/ violence	Transportation Incidents	Fire and explosions	Slips, trips, falls	Exposure to harmful substances, environments	Contact with objects, equipment	Cause not indicated	TOTAL
Likelihood Avg. (per 10,000 FTE)		0.014	0.614	0.043	0	0.057	0.171	0.2	1.1
Event Severity ($)		$9.5 million							
Configuration A	**Min**	0.003	0.144	0.01	0	0.013	0.04	0.047	0.258
Likelihood	**Avg**	0.005	0.2	0.014	0	0.019	0.056	0.065	0.359
	Max	0.006	0.283	0.02	0	0.026	0.079	0.092	0.506
Configuration A	**Min**	$28,500	$1368,000	$95,000	$0	$123,500	$380,000	$446,500	$2451,000
Risk ($)	**Avg**	$47,500	$1900,000	$133,000	$0	$180,500	$532,000	$617,500	$3410,500
	Max	$57,000	$2688,500	$190,000	$0	$247,000	$750,500	$874,000	$4807,000
Configuration B	**Min**	0.003	0.124	0.009	0	0.011	0.034	0.04	0.221
Likelihood	**Avg**	0.004	0.172	0.012	0	0.016	0.048	0.056	0.308
	Max	0.006	0.242	0.017	0	0.022	0.067	0.079	0.434
Configuration B	**Min**	$28,500	$1178,000	$85,500	$0	$104,500	$323,000	$380,000	$2099,500
Risk ($)	**Avg**	$38,000	$1634,000	$114,000	$0	$152,000	$456,000	$532,000	$2926,000
	Max	$57,000	$2299,000	$161,500	$0	$209,000	$636,500	$750,500	$4123,000
Configuration C	**Min**	0.0008	0.033	0.002	0	0.003	0.009	0.011	0.059
Likelihood	**Avg**	0.001	0.046	0.003	0	0.004	0.013	0.015	0.082
	Max	0.0015	0.065	0.005	0	0.006	0.018	0.021	0.116
Configuration C	**Min**	$7600	$313,500	$19,000	$0	$28,500	$85,500	$104,500	$560,500
Risk ($)	**Avg**	$9500	$437,000	$28,500	$0	$38,000	$123,500	$142,500	$779,000
	Max	$14,250	$617,500	$47,500	$0	$57,000	$171,000	$199,500	$1102,000
Configuration D	**Min.**	0.015	0.648	0.045	0	0.06	0.18	0.211	1.161
Likelihood	**Avg.**	0.021	0.9	0.063	0	0.084	0.251	0.293	1.613
	Max.	0.029	1.27	0.089	0	0.118	0.354	0.414	2.275
Configuration D	**Min.**	$140,315	$6153,815	$430,968	$0	$571,283	$1713,848	$2004,500	$11,024,750
Risk ($)	**Avg.**	$194,978	$8551,178	$598,861	$0	$793,839	$2381,517	$2785,400	$15,319,700
	Max.	$275,044	$12,062,644	$844,778	$0	$1119,822	$3359,466	$3929,200	$21,610,600

Notes: See Table 1. Event Severity is from EPA (United States Environmental Protection Agency (U.S. EPA) 2019) adjusted for inflation. Rounding of the risk and likelihood values causes the columns not to sum exactly to the reported total.

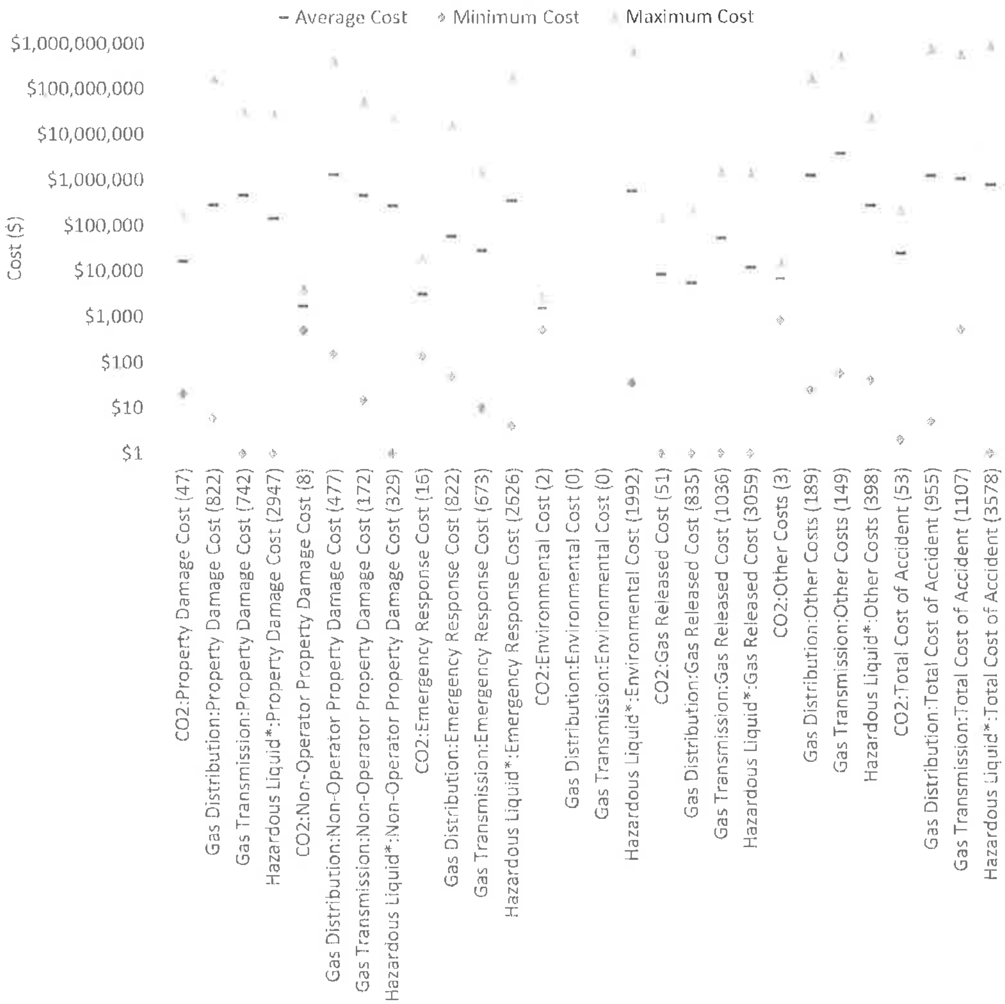

Fig. 2. Minimum, maximum and average costs by cost type for CO_2, gas distribution, gas transmission, and non-CO_2 hazardous liquids pipelines. Note: (the number in parentheses in each category along the x-axis is the number of incidents for that category.

Tables 3 and 4. Since the 1980s, between 750 miles and 900 miles of pipeline were constructed each decade. However, 74% of the accidents reported have occurred in pipelines constructed since 2010. Similar increases in accidents occur in all other pipeline systems, although it is most apparent for non-CO_2 hazardous liquid pipelines. Gas transmission line accidents increase by 1% from pipelines built in the 2000s compared to pipelines built since 2010. The percentage of pipeline miles, however, decreases by 4% from the 2000s to the 2010s. For hazardous liquid pipelines, 33% of accidents occur in pipelines built in the last decade, although only 16% of miles were constructed in 2010 and later.

4.3. *Quantitative risk*

The risks of pipeline construction and pipeline operations were quantitatively determined based on BLS (BLS 2017) data and the PHMSA hazardous liquid accidents database, which includes CO_2 pipelines.

4.3.1. *Pipeline construction*

Events causing hospitalization include intentional injury/violence; transportation incidents (i.e., traffic accidents or roadway and non-roadway vehicle incidents); fire and explosions; slips, trips, and falls; exposure to harmful substances and environments; contact with objects or equipment (including entanglement); overexertion/body reactions; and cause not indicated. The procedure to translate injury occurrence into project risk comprised the following steps:

- Determine the value of fulltime work equivalents (FTEs) required to complete the pipeline.
- Multiply the pipeline FTE by the injury rate per FTE to determine the likelihood of occurrence for each injury type.
- Calculate a dollar value to the severity of impact (consequence) of injuries based on lost wages due to time away from work, hospital stays, and potential litigation (estimated).
- Multiply the likelihood of occurrence by the value of the consequence to determine the risk in dollars.

The number and occurrence rate of injuries requiring hospitalization for the years between 2011 and 2017 for oil and gas pipeline construction (North American Industry Classification System [NAICS] Code 237,120) are included in Supplemental Data Table 5.

The FTEs needed to complete each pipeline configuration were determined based on the number of FTEs working and the number of pipelines constructed between the years 2011 and 2017. The number of FTEs were available from the US Census Bureau (United States Census

Table 3
Average likelihood (x 10,000 FTE) and risk for fatalities for pipeline Configurations A through D, by worker activity.

Worker Activity		Vehicle/ transport operations	Operation of tools/ machinery	Construction, repair, welding	Protective service	Material handling	Physical activity	Other	Activity not indicated	TOTAL
Likelihood Avg. (per 10,000 FTE)		0.614	0.086	0.129	0	0.014	0.043	0.014	0.2	1.1
Event Severity ($)		$9.5 million								
Configuration A Likelihood	Min	0.144	0.02	0.03	0	0.003	0.01	0.003	0.047	0.258
	Avg	0.2	0.028	0.042	0	0.005	0.014	0.005	0.065	0.359
	Max	0.283	0.04	0.059	0	0.006	0.02	0.006	0.092	0.506
Configuration A Risk ($)	Min	$1368,000	$190,000	$285,000	$0	$28,500	$95,000	$28,500	$446,500	$2451,000
	Avg	$1900,000	$266,000	$399,000	$0	$47,500	$133,000	$47,500	$617,500	$3410,500
	Max	$2688,500	$380,000	$560,500	$0	$57,000	$190,000	$57,000	$874,000	$4807,000
Configuration B Likelihood	Min	0.124	0.017	0.026	0	0.003	0.009	0.003	0.04	0.221
	Avg	0.172	0.024	0.036	0	0.004	0.012	0.004	0.056	0.308
	Max	0.242	0.034	0.051	0	0.006	0.017	0.006	0.079	0.434
Configuration B Risk ($)	Min	$1178,000	$161,500	$247,000	$0	$28,500	$85,500	$28,500	$380,000	$2099,500
	Avg	$1634,000	$228,000	$342,000	$0	$38,000	$114,000	$38,000	$532,000	$2926,000
	Max	$2299,000	$323,000	$484,500	$0	$57,000	$161,500	$57,000	$750,500	$4123,000
Configuration C Likelihood	Min	0.033	0.005	0.007	0	0.001	0.002	0.001	0.011	0.059
	Avg	0.046	0.006	0.01	0	0.001	0.003	0.001	0.015	0.082
	Max	0.065	0.009	0.014	0	0.001	0.005	0.001	0.021	0.116
Configuration C Risk ($)	Min	$313,500	$47,500	$66,500	$0	$9500	$19,000	$9500	$104,500	$560,500
	Avg	$437,000	$57,000	$95,000	$0	$9500	$28,500	$9500	$142,500	$779,000
	Max	$617,500	$85,500	$133,000	$0	$9500	$47,500	$9500	$199,500	$1102,000
Configuration D Likelihood	Min	0.648	0.091	0.136	0	0.015	0.045	0.015	0.211	1.161
	Avg	0.9	0.126	0.189	0	0.021	0.063	0.021	0.293	1.613
	Max	1.27	0.178	0.267	0	0.029	0.089	0.029	0.414	2.275
Configuration D Risk ($)	Min	$6153,815	$861,935	$1292,903	$0	$140,315	$430,968	$140,315	$2004,500	$11,024,750
	Avg	$8551,178	$1197,722	$1796,583	$0	$194,978	$598,861	$194,978	$2785,400	$15,319,700
	Max	$12,062,644	$1689,556	$2534,334	$0	$275,044	$844,778	$275,044	$3929,200	$21,610,600

Notes: See Table 1. Event severity is from EPA (United States Environmental Protection Agency (U.S. EPA) 2019) adjusted for inflation.

Table 4
CO_2 pipeline operations risks, including total, by pipeline specifications.

Factor	No. Acc.	Frac. (known only)[a]	Likelihood (per mi per year)[b]	Frac. Existing PL[c]	Norm. Likelihood (per mi per yr)[d]	Severity[e]		Risk per mile,per year[f]		30-Year Riskper mile[g]	
						Average	Median	Average	Median	Average	Median
Total	53	1	0.0011	1	0.0011	$23,808	$6334	$26.19	$6.97	$1246	$331
Area Type											
Above Ground	34	0.642	7.0×10^{-4}	0.08	5.63×10^{-3}	$4051	$1849	$22.82	$10.42	$1086	$496
Below Ground	19	0.358	3.9×10^{-4}	0.90	1.6×10^{-4}	$59,161	$17,500	$9.25	$2.74	$440	$130
Transition and Tanks	–	–	–	0.02	–	–	–	–	–	–	–
Installation Year											
Pre-1940	–	–	–	–	–	–	–	–	–	–	–
1940–49	–	–	–	–	–	–	–	–	–	–	–
1950–59	1	0.023	2.1×10^{-5}	0.01	4.81×10^{-5}	$96,002	$96,002	$4.61	$4.61	$219	$219
1960–69	4	0.093	8.3×10^{-5}	0.05	1.54×10^{-4}	$18,544	$13,750	$2.85	$2.11	$136	$101
1970–79	–	–	–	0.03	–	–	–	–	–	–	–
1980–89	3	0.070	6.2×10^{-5}	0.43	1.01×10^{-5}	$9667	$8877	$0.10	$0.09	$5	$4
1990–99	2	0.047	4.1×10^{-5}	0.17	1.13×10^{-5}	$37,360	$37,360	$0.42	$0.42	$20	$20
2000–09	4	0.093	8.3×10^{-5}	0.17	4.52×10^{-5}	$118,714	$125,105	$5.37	$5.66	$255	$269
2010–17	29	0.674	6.0×10^{-4}	0.14	2.89×10^{-3}	$16,398	$4215	$47.34	$12.17	$2252	$579
Material											
Steel	42	0.875	8.7×10^{-4}	0.99	7.7×10^{-4}	$28,756	$8275	$22.05	$6.35	$1049	$302
Plastic	–	–	–	0.0002	–	–	–	–	–	–	–
Other	6	0.125	1.2×10^{-4}	0.0095	1.6×10^{-3}	$4406	$1686	$7.19	$2.75	$342	$131

[a] Fraction of pipeline accidents meeting the condition. Records where the factor was not indicated were not used to determine the fraction.
[b] Number of accidents divided by miles of pipeline and years in database (9.24 years).
[c] Fraction of existing pipelines meeting condition. Data are from PHMSA (PHMSA 2019; PHMSA 2017, PHMSA 2017).
[d] Normalized likelihood found by multiplying likelihood (per mile per year) by the ratio between the fraction of accidents meeting the condition and the fraction of existing pipelines meeting the condition.
[e] Determined using entries in the database with reported costs only (i.e., entries with no reported costs were not assumed to be $0).
[f] Risk per mile, per year found by multiplying the normalized likelihood by severity. All risks rounded to nearest dollar.
[g] 30-year risk, assuming 3% annual inflation. All risks rounded to nearest dollar.

Bureau 2018) for the years 2011 to 2016. The FTEs for 2017 were calculated based on the ratio between the total number of injuries that occurred in each year and the occurrence rate for that year (see Supplemental data 5). The miles of pipeline constructed per year were estimated by taking the difference of the total mileage of pipeline operating, year over year, between 2010 and 2017 (PHMSA 2017)

Table 5
Natural gas distribution pipeline operations risks, including total, by pipeline specifications.

Factor	No. Acc.	Frac. (known only)	Likelihood (per mi per yr)	Frac. Existing PL	Norm. Likelihood (per mi per yr)	Severity		Risk per mile,per year		30-Year Riskper mile	
						Average	Median	Average	Median	Average	Median
Total	**974**	**1**	4.7×10^{-5}	**1**	4.7×10^{-5}	**$747,420**	**$86,034**	**$35.24**	**$4.06**	**$1676**	**$193**
Area Type											
Above Ground	390	0.400	1.9×10^{-5}	0.08	9.5×10^{-5}	$399,097	$78,861	$37.71	$7.45	$1794	$354
Below Ground	575	0.590	2.8×10^{-5}	0.90	1.8×10^{-5}	$1639,635	$90,946	$29.93	$1.66	$1424	$79
Transition and Tanks	9	0.010	4.4×10^{-7}	0.02	2.0×10^{-7}	$3679,054	$203,500	$0.74	$0.04	$35	$2
Installation Year											
Pre-1940	42	0.054	2.0×10^{-6}	0.03	4.1×10^{-6}	$412,627	$142,737	$1.68	$0.58	$80	$28
1940–49	25	0.032	1.2×10^{-6}	0.02	2.6×10^{-6}	$225,512	$74,708	$0.59	$0.19	$28	$9
1950–59	69	0.089	3.3×10^{-6}	0.07	4.2×10^{-6}	$658,106	$124,000	$2.79	$0.53	$133	$25
1960–69	111	0.143	5.4×10^{-6}	0.13	5.9×10^{-6}	$6958,354	$88,000	$40.82	$0.52	$1942	$25
1970–79	106	0.137	5.1×10^{-6}	0.11	6.4×10^{-6}	$260,269	$92,933	$1.66	$0.59	$79	$28
1980–89	113	0.146	5.5×10^{-6}	0.14	5.8×10^{-6}	$423,298	$90,946	$2.46	$0.53	$117	$25
1990–99	122	0.157	5.9×10^{-6}	0.20	4.6×10^{-6}	$505,801	$78,586	$2.35	$0.36	$112	$17
2000–09	104	0.134	5.0×10^{-6}	0.18	3.8×10^{-6}	$455,828	$84,399	$1.71	$0.32	$81	$15
2010–17	84	0.108	4.1×10^{-6}	0.13	3.4×10^{-6}	$312,143	$60,770	$1.06	$0.21	$50	$10
Material											
Steel	440	0.466	2.1×10^{-5}	0.33	3.0×10^{-5}	$415,013	$86,218	$12.48	$2.59	$594	$123
Plastic	304	0.322	1.5×10^{-5}	0.65	7.4×10^{-6}	$416,701	$84,399	$3.06	$0.62	$146	$29
Other	200	0.212	9.7×10^{-6}	0.03	8.2×10^{-5}	$3575,073	$87,533	$293.31	$7.18	$13,954	$342

Notes: See Table 4 for column descriptions.

(Supplemental Data Table 6). Because there is no accurate accounting of the mileage of pipeline constructed in a year, these values had to be calculated by using the year-over-year difference of pipelines in operation. The actual miles of pipeline constructed are likely higher because this method does not account for pipelines that went offline; thus, this process provides a conservative estimate for the resulting risk of pipeline construction. The resulting mileage constructed and FTE values were used to estimate the minimum, average, and maximum number of FTEs needed to construct each of the pipeline configurations (Table 1). The number of FTEs needed to construct each pipeline was then multiplied by the average occurrence of each injury to estimate risk.

Cost was calculated by assigning dollar values to the following consequences of each injury requiring hospitalization:

- *Lost wages:* $6537.90
  - o The US Census Bureau (United States Census Bureau 2018) shows average annual rates for NAICS Code 237,120 to be $81,723.74.
  - o The median days away from work for all injuries was 20 days (Bureau of Labor and Statistics (BLS) 2018).
- *Hospitalization:* A three-day hospital stay was assumed for slips, trips, and falls; exposure to harmful substances or environments; contact with objects or equipment; and overexertion and body reaction with a cost of $30,000. A seven-day hospital stay was assumed for intentional injury/violence; transportation incidents; and fire and explosions at a cost of $70,000. The estimated daily cost of a hospital stay is from healthcare.gov (Department of Health and Human Services (nd)).
- *Potential litigation:* $150,000 (estimate).

Table 6
Natural gas transmission/gathering pipeline operations risks, including total, by pipeline specifications.

Factor	No. Acc.	Frac. (known only)	Likelihood (per mi per yr)	Frac. Existing PL	Norm. Likelihood (per mi per yr)	Severity		Risk per mile,per year		30-Year Riskper mile	
						Average	Median	Average	Median	Average	Median
Total	**1113**	**1**	0.0004	**1**	0.0004	**$1016,144**	**$121,661**	**$383.96**	**$45.97**	**$18,266**	**$2187**
Area Type											
Above Ground	455	0.478	1.5×10^{-4}	0.08	9.3×10^{-4}	$362,839	$48,063	$335.20	$44.40	$15,947	$2112
Below Ground	483	0.508	1.6×10^{-4}	0.90	9.3×10^{-5}	$1811,561	$180,145	$167.63	$16.67	$7975	$793
Transition and Tanks	13	0.014	4.4×10^{-6}	0.02	3.0×10^{-6}	$932,013	$300,002	$2.81	$0.90	$134	$43
Installation Year											
Pre-1940	34	0.034	1.2×10^{-5}	0.03	1.5×10^{-5}	$234,354	$116,752	$3.44	$1.71	$164	$81
1940–49	77	0.078	2.6×10^{-5}	0.02	1.4×10^{-4}	$446,273	$150,000	$60.43	$20.31	$2875	$966
1950–59	155	0.156	5.3×10^{-5}	0.07	1.2×10^{-4}	$4031,113	$146,972	$473.97	$17.28	$22,549	$822
1960–69	172	0.174	5.8×10^{-5}	0.13	7.7×10^{-5}	$839,909	$200,693	$64.98	$15.53	$3091	$739
1970–79	172	0.174	5.8×10^{-5}	0.11	9.2×10^{-5}	$533,314	$258,885	$49.14	$23.85	$2338	$1135
1980–89	87	0.088	3.0×10^{-5}	0.14	1.9×10^{-5}	$386,720	$96,925	$7.32	$1.83	$348	$87
1990–99	77	0.078	2.6×10^{-5}	0.20	1.0×10^{-5}	$256,273	$80,591	$2.60	$0.82	$124	$39
2000–09	102	0.103	3.5×10^{-5}	0.18	2.0×10^{-5}	$862,540	$81,619	$17.08	$1.62	$813	$77
2010–17	115	0.116	3.9×10^{-5}	0.13	3.5×10^{-5}	$546,392	$54,396	$19.04	$1.90	$906	$90
Material											
Steel	1046	0.940	3.6×10^{-4}	0.992	3.4×10^{-4}	$1053,033	$128,085	$354.16	$43.08	$16,849	$2049
Plastic	1	0.001	3.4×10^{-7}	0.007	4.2×10^{-8}	$26,105	$26,105	$0.00	$0.00	<$1	<$1
Other	66	0.059	2.2×10^{-5}	0.001	2.7×10^{-3}	$446,515	$42,658	$1186.56	$113.36	$56,450	$5393

Notes: See Table 4 for column descriptions.

The final cost of injuries related to slips, trips, and falls; exposure to harmful substances or environments; contact with objects or equipment; and overexertion/body reaction was $186,538. The final cost for intentional injury/violence, transportation incidents, and fire and explosions was $226,538.

Events resulting in the highest risk for each pipeline include contact with objects or equipment, which accounted for approximately half the cost of risk for each of the configurations due to the high rate of occurrence; overexertion/body reaction, which accounted for just under one-quarter of the cost of risk for each of the configurations due to the high rate of occurrence; and transportation incidents, which accounted for around 13% of the cost of risk for each of the configurations due to the high rate of occurrence and higher cost of consequence.

Event/exposures causing fatalities include intentional injury/violence; transportation incidents (i.e., traffic accidents or roadway and non-roadway vehicle incidents); fire and explosions; slips, trips, and falls; exposure to harmful substances and environments; contact with objects or equipment (including entanglement); and cause not indicated. Supplemental Data Table 8 presents the number of fatalities and occurrence rate of fatalities for the years between 2011 and 2017 for oil and gas pipeline construction (NAICS Code 237,120).

To determine the overall risk posed by fatalities, a similar process to the one used to determine the risk posed by injuries was implemented. The values of FTE required to complete each of the four pipeline configurations was the same as those used for the injuries requiring hospitalization. The number of fatalities likely for each pipeline configuration was found by multiplying the number of workers needed by the incidence rates of fatalities for each event/exposure and worker activity. The cost of the consequence of a fatality was determined using the standard US EPA valuation for a human life ($7.4 million in 2006 dollars (United States Environmental Protection Agency (U.S. EPA) 2019)) updated to $9.5 million in 2019 dollars.

The risk for each of the four configurations, found by multiplying the number of FTEs likely to suffer a fatality by the cost of a fatality, is presented by event/exposure in Table 2 and by worker activity in Table 3. The minimum, average, and maximum risk of fatality for each pipeline configuration is also presented.

4.3.2. Pipeline operations

CO_2, natural gas distribution, natural gas transmission/gathering, and non-CO_2 hazardous pipeline operations risks were calculated using the data provided by PHSMA (Pipeline and Hazardous Materials Safety Administration 2019). Average and median costs were used to determine the risk for each pipeline type. Average and median costs were calculated for all accidents/incidents as well as for pipeline specifications and accident/incident types. For pipeline specifications, the likelihood of the occurrence of accidents/incidents (per mile, per year) needed to be normalized because the specification data of pipelines are not evenly distributed. For example, more than 99% of CO_2 pipelines are steel; however, an eighth of accidents at CO_2 pipelines occurred in material other than steel, meaning accidents occurred in pipelines composed of other materials proportionally more often than in steel pipelines. Normalization was done by multiplying the ratio between the fraction of accidents/incidents that occurred at pipelines of the specification and the percentage of existing pipelines that meet the specification.

Tables 4–7 show the total pipeline operations risks and risk by pipeline specification for CO_2 pipelines, gas distribution, gas transmission, and non-CO_2 hazardous liquid pipelines, respectively. Average and median risks were determined by determining the occurrence of accidents/incidents reported from 2010 to 2017 (Pipeline and Hazardous Materials Safety Administration 2019). The likelihood of pipeline risks was found by dividing the total number of accidents/incidents by pipeline mileage (PHMSA 2017) and the number of years in the database (9.24 years).

Average severity and median severity were found for each pipeline type and specification by determining the average and median total costs of each accident, reported by the PHMSA database. Average and median risk was per mile per year and was found by multiplying the normalized likelihood by the average and median severity, respectively. Because the CO_2 pipeline for the proposed commercial-scale project will operate for 30 years, the 30-year-per-mile risk was also found, assuming 3% annual inflation.

The average and maximum total risk is less for CO_2 pipelines than for natural gas distribution pipelines, natural gas transmission/gathering pipelines, and non-CO_2 hazardous liquid pipelines (Tables 4 through 7).

Accident/incident type (release type, release cause, and item

Table 7
Non-CO_2 hazardous liquid pipeline operations risks, including total, by pipeline specifications.

Factor	No. Acc.	Frac. (known only)	Likelihood (per mi per yr)	Frac. Existing PL	Norm. Likelihood (per mi per yr)	Severity		Risk per mile,per year		30-Year Riskper mile	
						Average	Median	Average	Median	Average	Median
Total	3603	1	0.0019	1	0.0019	$743,280	$25,020	$1376.35	$46.33	$65,478	$2204
Area Type											
Above Ground	1927	0.54	1.0×10^{-3}	0.08	6.7×10^{-3}	$103,798	$10,000	$697.30	$67.18	$33,173	$3196
Below Ground	1225	0.34	6.3×10^{-4}	0.90	2.4×10^{-4}	$1916,164	$95,176	$457.64	$22.73	$21,772	$1081
Transition and Tanks	426	0.12	2.2×10^{-4}	0.02	1.3×10^{-3}	$263,219	$32,617	$342.11	$42.39	$16,276	$2017
Installation Year											
Pre-1940	54	0.03	3.0×10^{-5}	0.04	1.8×10^{-5}	$513,973	$146,094	$9.36	$2.66	$445	$127
1940–49	100	0.04	5.1×10^{-5}	0.08	3.0×10^{-5}	$1602,635	$72,202	$48.73	$2.20	$2318	$104
1950–59	253	0.11	1.3×10^{-4}	0.17	8.7×10^{-5}	$1145,943	$122,647	$99.13	$10.61	$4716	$505
1960–69	235	0.11	1.2×10^{-4}	0.17	7.6×10^{-5}	$4789,977	$155,050	$366.04	$11.85	$17,414	$564
1970–79	236	0.11	1.2×10^{-4}	0.15	8.8×10^{-5}	$961,283	$94,262	$84.74	$8.31	$4032	$395
1980–89	131	0.06	6.7×10^{-5}	0.07	5.4×10^{-5}	$468,162	$76,269	$25.09	$4.09	$1194	$194
1990–99	180	0.08	9.3×10^{-5}	0.09	8.4×10^{-5}	$2081,149	$84,160	$175.08	$7.08	$8329	$337
2000–09	292	0.13	1.5×10^{-4}	0.08	2.5×10^{-4}	$505,768	$31,508	$127.76	$7.96	$6078	$379
2010–17	743	0.33	3.8×10^{-4}	0.16	7.9×10^{-4}	$200,993	$14,450	$158.28	$11.38	$7530	$541
Material											
Steel	2293	0.800	1.2×10^{-3}	0.9903	9.5×10^{-4}	$1119,927	$50,266	$1066	$48	$50,727	$2277
Plastic	-	–	–	0.0002	–	$0	$0	$0	$0	$0	$0
Other	573	0.200	2.9×10^{-4}	0.0095	6.2×10^{-3}	$177,122	$14,450	$1098	$90	$52,223	$4260

Notes: See Table 4 for column descriptions.

involved) was also determined for each pipeline type. These results are presented in Tables 8–11. Because accident type is not a specification of a pipeline, these risks were not normalized in the same way that pipeline specifications were. The risk of each accident/incident type was found by multiplying the likelihood of the accident type by the average and median severity for each accident type.

The average and median 30-year operation risks were found for each of the pipeline configurations for each pipeline type (Table 12) by multiplying the average and median overall severity of each pipeline type by the overall likelihood of accident/incident occurrence of each pipeline type. While the average value presents a more reasonable risk, the maximum value provides the worst-case scenario in which all accidents occurring at each pipeline are given the worst possible outcome for the pipeline type that is presented in the PHMSA database.

5. Discussion

Pipeline construction and operation risks were estimated using accident data from PHMSA. The average risks for construction and 30 years of operation of the four CO_2 pipeline configurations were found by summing the risk of fatalities and injuries during construction and the risk of 30-year operation. They averaged between $1400,521 for the shorter (79 miles) pipeline connecting nearby power plants to the proposed sinks and $27,481,939 for a longer pipeline (1546 miles) connecting numerous ethanol plants and power sources throughout Nebraska to the sinks in southwest Nebraska and western Kansas. The average 30-year operating risk is $98,434 for the shorter pipeline (79 miles) and $1926,316 for the longer pipeline (1546 miles). Pipeline construction accounts for most of the risk, with injury during construction accounting for 37.2% of project risk and fatality during construction accounting for 55.8% of project risk. The remaining 7.0% of risk is due to 30 years of pipeline operations.

In contrast, 30-year operation estimates of gas distribution pipelines, gas transmission pipelines, and non-CO_2 hazardous liquid pipelines with the same routes accounted for a higher amount of project risk compared to pipeline construction. For gas distribution pipelines, the 30-year project risk ranged from $132,404 to $2591,096. For gas distribution pipelines, construction accounted for most of the risk, with injury during construction accounting for 36.4% of project risk and fatality during construction accounting for 54.4% of project risk. The remaining 9.2% of risk is 30 years of pipeline operations. For gas transmission pipelines, the 30-year project risk ranged from $1443,014 to $28,239,236. For gas transmission pipelines, construction accounted for a little less than half the risk, with injury during construction accounting for 19.0% of project risk and fatality during construction accounting for 28.5% of project risk. The remaining 52.5% of risk is for 30 years of pipeline operations. For non-CO_2 hazardous liquid pipelines, the 30-year project risk ranged from $5172,762 to $101,228,988. For non-$CO_2$ hazardous liquid pipelines, construction accounted for around 20% of the project risk, with injury during construction accounting for 8.1% of project risk and fatality during construction accounting for 12.1% of project risk. The remaining 79.8% of risk is for 30 years of pipeline operations. This indicates that CO_2 pipelines are less risky to operate than the other three pipeline types analyzed in this study, and as a result, the construction is by far the riskiest part of a CO_2 pipeline project. This is particularly true for gas transmission and non-CO_2 hazardous liquid pipelines for which operations account for 52.5% and 79.8% of total pipeline project risks, respectively.

Project risks were largely estimated using average values. Because costs of accidents ranged by several orders of magnitude with some incidents at gas distribution, gas transmission, and non-CO_2 hazardous liquid pipelines resulting in hundreds of millions of dollars in damage, averages can be skewed to higher amounts for these pipelines. The same is true for CO_2 pipelines, although the effect is not as dramatic. The median values of the total cost of an accident were consistently less than average values, sometimes by more than an order of magnitude (see supplemental data). While average values may skew toward higher reported risks, they provide a conservative estimate of project risks that is still reasonable. Using a maximum value of damages to determine event severity would provide unrealistic risk values on the order of hundreds of billions of dollars for non-CO_2 hazardous liquid pipelines, precluding their construction. Risk of CO_2 pipelines calculated using maximum values would indicate project operation risks on the order of tens of millions of dollars for a 1500-mile pipeline, an unrealistic estimate given the severity of reported incidents in the database used for this project. Alternatively using minimum values to determine risk is also unrealistic due to a limited number of incidents that have reported damages ranging from $1 to $20.

Because incident reporting is done by pipeline operators themselves, unreported or underreported incidents at CO_2 pipelines could affect our results, making CO_2 pipeline accidents appear less likely than they are. The requirements of reporting outlined in Section 3.0 should help

Table 8
CO_2 pipeline operations risks by accident type.

Factor	No. Acc.	Frac. (known only)	Likelihood (per mi per yr)	Severity		Risk per mile, per year		30-Year Risk per mile	
				Average	Median	Average	Median	Average	Median
Release Type									
Leak	46	0.87	9.5×10^{-4}	$18,831	$5676	$17.90	$5.40	$852	$257
Mechanical Puncture	–	–	–	–	–	–	–	–	–
Rupture	2	0.04	4.1×10^{-5}	$108,464	$108,464	$4.48	$4.48	$213	$213
Other	5	0.09	1.0×10^{-4}	$35,735	$3510	$3.69	$0.36	$176	$17
Release Cause									
Corrosion	7	0.13	1.5×10^{-4}	$11,934	$10,065	$1.73	$1.46	$82	$69
Equipment Failure	26	0.49	5.4×10^{-4}	$7382	$1669	$3.97	$0.90	$189	$43
Excavation	–	–	–	–	–	–	–	–	–
Incorrect Operation	7	0.13	1.5×10^{-4}	$28,816	$4215	$4.17	$0.61	$198	$29
Material Failure	9	0.17	1.9×10^{-4}	$84,797	$67,675	$15.77	$12.59	$750	$599
Outside Force	1	0.02	2.1×10^{-5}	$15,817	$15,817	$0.33	$0.33	$16	$16
Other	3	0.06	6.2×10^{-5}	$1878	$1525	$0.12	$0.09	$6	$4
Item Involved									
Auxiliary pipeline or relief line	3	0.06	6.2×10^{-5}	$10,759	$8877	$0.67	$0.55	$32	$26
Pipe	13	0.25	2.7×10^{-4}	$57,841	$16,000	$15.54	$4.30	$739	$204
Valve	23	0.43	4.8×10^{-4}	$7579	$1641	$3.60	$0.78	$171	$37
Weld	4	0.08	8.3×10^{-5}	$68,732	$43,364	$5.68	$3.58	$270	$171
Other	10	0.19	2.1×10^{-4}	$28,367	$2563	$5.86	$0.53	$279	$25

Notes: See Table 4 for column descriptions. Fraction of existing pipelines and normalized likelihood columns are not applicable to accident type. Per year risk is found by multiplying likelihood (per mile per year) by severity.

Table 9
Natural gas distribution pipeline operations risks by accident type.

Factor	No. Acc.	Frac. (known only)	Likelihood (per mi per yr)	Severity		Risk per mile, per year		30-Year Risk per mile	
				Average	Median	Average	Median	Average	Median
Release Type									
Leak	293	0.30	1.4×10^{-5}	$346,959	$95,500	$4.92	$1.35	$234	$64
Mechanical Puncture	271	0.28	1.3×10^{-5}	$414,773	$94,027	$5.44	$1.23	$259	$59
Rupture	46	0.05	2.2×10^{-6}	$197,579	$77,151	$0.44	$0.17	$21	$8
Other	364	0.37	1.8×10^{-5}	$2495,600	$75,583	$43.97	$1.33	$2092	$63
Release Cause									
Corrosion	21	0.08	1.0×10^{-6}	$154,278	$75,494	$0.16	$0.08	$7	$4
Equipment Failure	49	0.05	2.4×10^{-5}	$242,587	$70,514	$0.58	$0.17	$27	$8
Excavation	290	0.28	1.4×10^{-5}	$456,963	$96,390	$6.41	$1.35	$305	$64
Incorrect Operation	67	0.06	3.2×10^{-6}	$11,162,488	$32,501	$36.20	$0.11	$1722	$5
Material Failure	66	0.06	3.2×10^{-6}	$198,297	$135,505	$0.63	$0.43	$30	$21
Outside Force	390	0.37	1.9×10^{-5}	$370,640	$80,587	$7.00	$1.52	$333	$72
Other	91	0.09	4.4×10^{-6}	$861,317	$84,331	$3.79	$0.37	$180	$18
Item Involved (Not applicable to Gas Distribution pipelines)									
Unintentional Release of Gas	868	0.89	4.2×10^{-5}	$412,259	$90,917	$17.32	$3.82	$824	$182
Intentional Release of Gas	12	0.01	5.8×10^{-7}	$553,489	$10,208	$0.32	$0.01	$15	<$1
Reasons other than Release of Gas	94	0.10	4.6×10^{-6}	$8160,282	$50,412	$37.13	$0.23	$1766	$11

Notes: See Table 4 for column descriptions. Fraction of existing pipelines and normalized likelihood columns are not applicable to accident type. Per year risk is found by multiplying likelihood (per mile per year) by severity.

Table 10
Natural gas transmission/gathering pipeline operations risks by accident type.

Factor	No. Acc.	Frac (known only)	Likelihood (per mi per yr)	Severity		Risk per mile, per year		30-Year Risk per mile	
				Average	Median	Average	Median	Average	Median
Release Type									
Leak	461	0.41	1.6×10^{-4}	$343,112	$194,074	$53.70	$30.37	$2555	$1445
Mechanical Puncture	110	0.10	3.7×10^{-5}	$376,386	$101,714	$14.06	$3.80	$669	$181
Rupture	147	0.13	5.0×10^{-5}	$5244,512	$447,500	$261.73	$22.33	$12,452	$1062
Other	395	0.35	1.3×10^{-4}	$406,198	$47,693	$54.47	$6.40	$2591	$304
Release Cause									
Corrosion	222	0.20	7.5×10^{-5}	$661,647	$277,181	$49.87	$20.89	$2372	$994
Equipment Failure	347	0.31	1.2×10^{-4}	$248,702	$48,382	$29.30	$5.70	$1394	$271
Excavation	142	0.13	4.8×10^{-5}	$403,263	$105,130	$19.44	$5.07	$925	$241
Incorrect Operation	62	0.06	2.1×10^{-5}	$419,544	$82,750	$8.83	$1.74	$420	$83
Material Failure	126	0.11	4.3×10^{-5}	$5134,120	$250,001	$219.62	$10.69	$10,448	$509
Outside Force	154	0.14	5.2×10^{-5}	$871,732	$129,007	$45.58	$6.74	$2168	$321
Other	60	0.05	2.0×10^{-5}	$627,081	$124,717	$12.77	$2.54	$608	$121
Item Involved									
Auxiliary pipeline or relief line	44	0.04	1.5×10^{-5}	$249,943	$72,132	$3.73	$1.08	$178	$51
Pipe	508	0.46	1.7×10^{-4}	$1811,162	$213,999	$312.36	$36.91	$14,860	$1756
Valve	215	0.19	7.3×10^{-5}	$243,908	$51,010	$17.80	$3.72	$847	$177
Weld	58	0.05	2.0×10^{-5}	$610,044	$224,831	$12.01	$4.43	$571	$211
Other	288	0.26	9.8×10^{-5}	$389,161	$70,396	$38.05	$6.88	$1810	$327
Incident Result									
Unintentional Release	868	0.89	4.2×10^{-5}	$973,148	$125,521	$40.89	$5.27	$1945	$251
Intentional Release	12	0.01	5.8×10^{-7}	$142,005	$89,278	$0.08	$0.05	$4	$2
Reasons other than Release of Gas	94	0.10	4.6×10^{-6}	$2238,142	$121,577	$10.18	$0.55	$484	$26

Notes: See Table 4 for column descriptions. Fraction of existing pipelines and normalized likelihood columns are not applicable to accident type. Per year risk is found by multiplying likelihood (per mile per year) by severity.

prevent unreported or underreported incidents; however, additional information about reporting of incidents could help to lend confidence to the values used in this analysis. In addition, estimates of the severity of consequences may be suspect. For instance, some of the releases of CO_2 in our database had questionable estimates for the cost of gas released. A detailed analysis of the underlying cost assumptions based on a close review of the detailed accident reports may help improve these estimates.

Construction risks could also be improved with additional information. The calculations of the miles of pipeline constructed per FTE are likely low due to the way that the mileage of pipeline constructed annually was estimated in this study. A data source that has an accurate accounting of the new pipeline construction for the years of interest would improve these estimates. In addition, identifying specific worker categories beyond the BLS NAICS could also help to identify workers at higher risk of injuries or fatalities from constructing pipelines. For instance, a general laborer may be at a higher risk than the job foreman or a heavy machine operator. Identifying the individuals at greatest risk could help target risk mitigation efforts.

Past data for pipeline risks were reviewed to determine the likelihood of the scenarios and the resulting consequences. Only 53 releases were documented for the period of review (2010–2017), suggesting releases from CO_2 pipelines are rare. When normalized by mile, the likelihood of accidents occurring on CO_2 pipelines is higher than those of

Table 11
Non-CO_2 hazardous liquid pipeline operations risks by accident type.

Factor	No. Acc.	Frac (known only)	Likelihood (per mi per yr)	Severity		Risk per mile, per year		30-Year Risk per mile	
				Average	Median	Average	Median	Average	Median
Release Type									
Leak	2807	0.78	1.4×10^{-3}	$377,295	$25,045	$544.30	$36.13	$25,894	$1719
Mechanical Puncture	119	0.03	6.1×10^{-5}	$992,937	$235,000	$60.73	$14.37	$2889	$684
Rupture	87	0.02	4.5×10^{-5}	$13,568,390	$723,215	$606.68	$32.34	$28,862	$1538
Other	590	0.17	3.0×10^{-4}	$542,984	$10,950	$164.65	$3.32	$7833	$158
Release Cause									
Corrosion	727	0.24	3.7×10^{-4}	$664,662	$54,000	$248.34	$20.18	$11,815	$960
Equipment Failure	1643	0.40	8.4×10^{-4}	$108,167	$11,007	$91.34	$9.29	$4345	$442
Excavation	136	0.03	7.0×10^{-5}	$1153,741	$222,809	$80.64	$15.57	$3836	$741
Incorrect Operation	502	0.12	2.6×10^{-4}	$247,279	$12,500	$63.80	$3.22	$3035	$153
Material Failure	255	0.12	1.3×10^{-4}	$4746,409	$158,934	$622.04	$20.83	$29,593	$991
Outside Force	233	0.06	1.2×10^{-4}	$1781,395	$65,770	$213.32	$7.88	$10,148	$375
Other	107	0.03	5.5×10^{-5}	$1034,265	$40,050	$56.88	$2.20	$2706	$105
Item Involved									
Auxiliary pipeline or relief line	246	0.07	1.3×10^{-4}	$148,824	$14,532	$18.82	$1.84	$895	$87
Pipe	901	0.25	4.6×10^{-4}	$2259,541	$116,860	$1046.30	$54.11	$49,777	$2574
Valve	644	0.18	3.3×10^{-4}	$120,646	$15,013	$39.93	$4.97	$1900	$236
Weld	146	0.04	7.5×10^{-5}	$1544,425	$114,538	$115.89	$8.59	$5513	$409
Other	1666	0.46	8.6×10^{-4}	$145,198	$11,956	$124.32	$10.24	$5914	$487

Notes: See Table 4 for column descriptions. Fraction of existing pipelines and normalized likelihood columns are not applicable to accident type. Per year risk is found by multiplying likelihood (per mile per year) by severity.

Table 12
Total pipeline risk for 30 years of operation for the four pipeline configurations (with 3% annual inflation), by pipeline type.

Configuration	Mile-age	CO_2		Gas Distribution		Gas Transmission/Gathering		Non-CO_2 Haz. Liquid	
		Average	Median	Average	Median	Average	Median	Average	Median
Risk per mile	–	$26.19	$6.97	$35.24	$4.06	$383.96	$45.97	$1376.35	$46.33
30-year project	–	$1246	$331	$1676	$193	$18,266	$2187	$65,478	$2204
A	344	$428,624	$113,864	$576,544	$66,392	$6283,504	$752,328	$22,524,432	$758,176
B	295	$367,570	$97,645	$494,420	$56,935	$5388,470	$645,165	$19,316,010	$650,180
C	79	$98,434	$26,149	$132,404	$15,247	$1443,014	$172,773	$5172,762	$174,116
D	1546	$1926,316	$511,726	$2591,096	$298,378	$28,239,236	$3381,102	$101,228,988	$3407,384

gas distribution or gas transmission pipelines. This is likely due to the lower threshold for reporting leaks from hazardous liquid pipelines (CO_2 pipelines are considered hazardous liquid pipelines), which is 5 barrels, compared to that of gas pipelines, which is 3 million cubic feet or more. The consequences of the events reported from CO_2 pipelines were also very minor compared to other non-CO_2 hazardous liquid pipelines, gas distribution pipelines, and gas transmission pipelines.

CO_2 leakage risks can be mitigated by using effective operations controls and designs. CO_2 pipelines are required to be constructed of materials compatible with CO_2. This, combined with making sure dry gas is running through the pipeline, can help to mitigate corrosion and other material failure, which accounted for 30% of the accidents reported in the PHMSA database. Understanding the expected lifetime of pipeline equipment and a rigid maintenance schedule can help to mitigate issues related to equipment failure, which accounted for nearly half the accidents reported at CO_2 pipelines. Proper training of employees who operate pipelines could help mitigate the third most common cause of accidents reported in the PHMSA database—incorrect operation—-which accounted for 13% of the reported accidents.

Quick identification of release accidents could also help to mitigate the worst consequences of pipeline leaks. The most effective accident identifier for CO_2 pipelines was people, who identified nearly 80% of the accidents reported in the database. While computerized monitoring may be an important technology for monitoring CO_2 pipelines, it should not replace ground patrols, air patrols, or reports solicited from third parties or the public. This also helps inform mitigation techniques, which should include regular ground and air patrols by pipeline personnel and visible postings of contact information to pipeline operators, so that accidents can be easily and readily reported by the public.

The cost of the 53 release accidents at CO_2 pipelines was correlated with the amount of gas released, particularly the amount of gas intentionally released (Fig. 3). The R^2-values for plots of accident costs versus the total amount of gas released and the amount of gas intentionally released were 0.7844 and 0.7545, respectively. Conversely, the R^2-value of the plot of total cost of the accident versus the amount of gas unintentionally released was <0.01. When the accidents were restricted to reportable incidents (i.e., incidents with unintentional releases >5 bbls), the R^2-values for the plots of total cost of accident versus the total gas released and the gas intentionally released dropped to 0.5275 and 0.461, respectively. The R^2-value for the plot of total cost versus gas unintentionally released was still <0.01.

For each type of system, the accidents per mile increased for each decade installed from the 1990s through 2017 (Fig. 4). Although CO_2 pipelines had the highest accidents per mile for recently constructed pipelines, the accidents per mile become much lower than for hazardous liquids and much more comparable to gas transmission for pre-2010 pipelines. The increase in accidents in newer pipelines could be attributed to human errors. Installation errors that cause equipment failure are often not noticed until they cause an accident. This would likely happen in less than a decade, but the operator can correct the issue and expect risk of equipment failure to be decreased long term. There is also increased risk for operator error with a new pipeline due to inexperience.

The number and severity (adjusted for inflation) of CO_2 pipeline accidents, by pipeline age, from the 1990s onward from PHMSA (Pipeline and Hazardous Materials Safety Administration 2019) are shown in Fig. 5. The number of incidents is initially high; 21 of 74 reported accidents occurred within one year of pipeline installation, and an

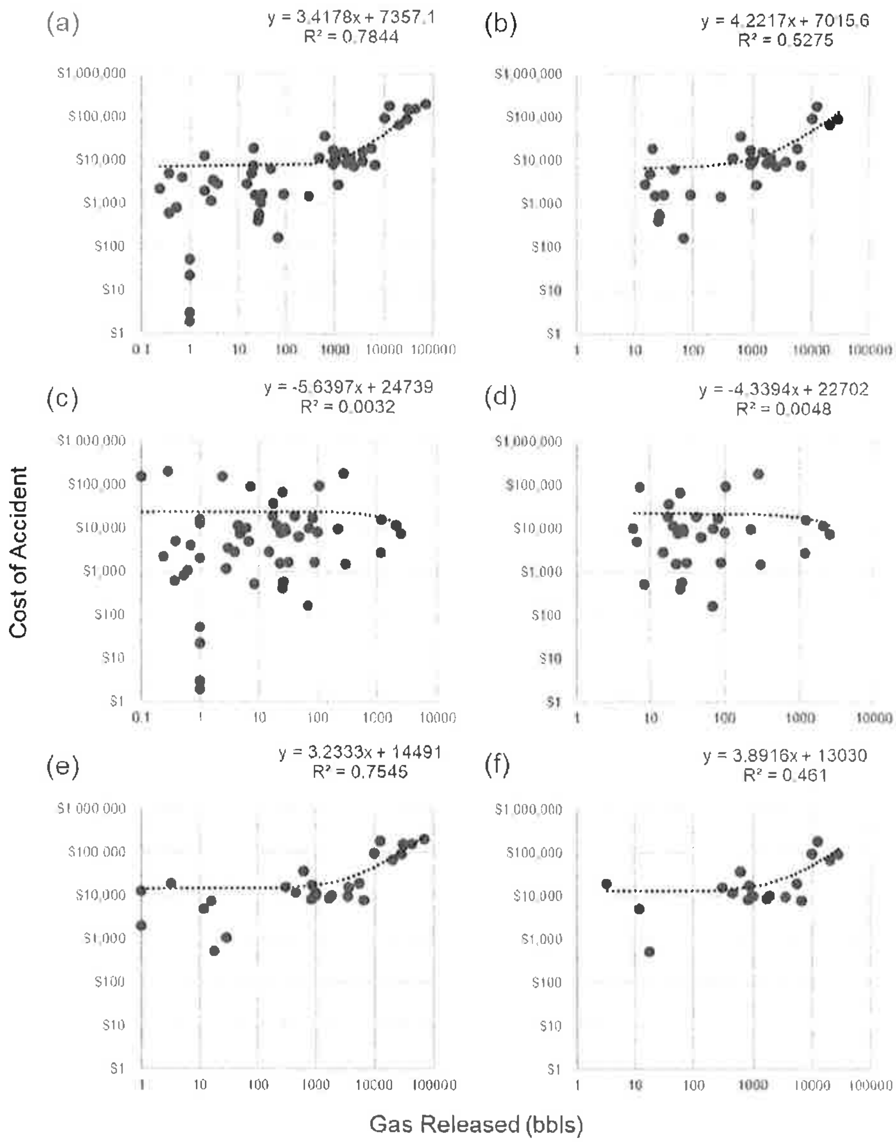

Fig. 3. Total cost of incident for CO_2 pipeline plotted against the amount of gas released for the following: (a) total amount of gas released, (b) total amount of gas released for reportable incidents (>5 bbls unintentionally released), (c) amount of gas unintentionally released, (d) amount of gas unintentionally released for reportable incidents, (e) amount of gas intentionally released, and (f) amount of gas released for reportable incidents.

additional 20 reported accidents occurred within two to five years of pipeline installation (average of five accidents per year). The number of incidents then decreases to between 0.4 and 1.6 incidents after five years. The severity of accidents follows a bathtub curve typical of reliability engineering. The severity was initially high (average of $100,259 per accident) and drops to less than $50,000 for pipeline ages between 2 and 50 years old and increases to $100,802 for the accident in a pipeline more than 50 years old.

Opposition to pipelines is also an important consideration for effective project implementation. An effective outreach plan may help to mitigate some local opposition. Outreach plans should be tailored to the socioeconomic makeup of the residents that the project personnel are trying to reach. Outreach needs to address project risk and benefits in a clear, concise manner. CCUS projects have the advantage of providing actual and perceived benefits to different types of stakeholders. Many environmental NGOs focusing on climate change and local residents who are worried about a warmer future may see the benefits of a CCUS project, particularly because the Intergovernmental Panel on Climate Change (IPCC) finds that CCUS is an important technology to curb the worst effects of climate change while minimizing the economic impact (Intergovernmental Panel on Climate Change (IPCC) 2014).

Local residents, industry, and trade groups not focused on climate change could see the benefits to local economies, job growth, and infrastructure development. For a pipeline plan to be effective, these benefits must be shared among residents along the entire pipeline instead of just those at the source and sink locations. An integrated statewide hub like the one proposed in the IMSCS-HUB project could help ensure that all areas along the pipeline are benefiting from its development. In addition, taking advantage of existing pipeline rights-of-way (ROWs) may help mitigate the risk of local opposition due to the use of eminent domain. Where it is not possible to use existing pipeline ROWs, fair compensation to landowners through easements is necessary to keep residents in support of a project.

NGOs are an important consideration when dealing with pipeline

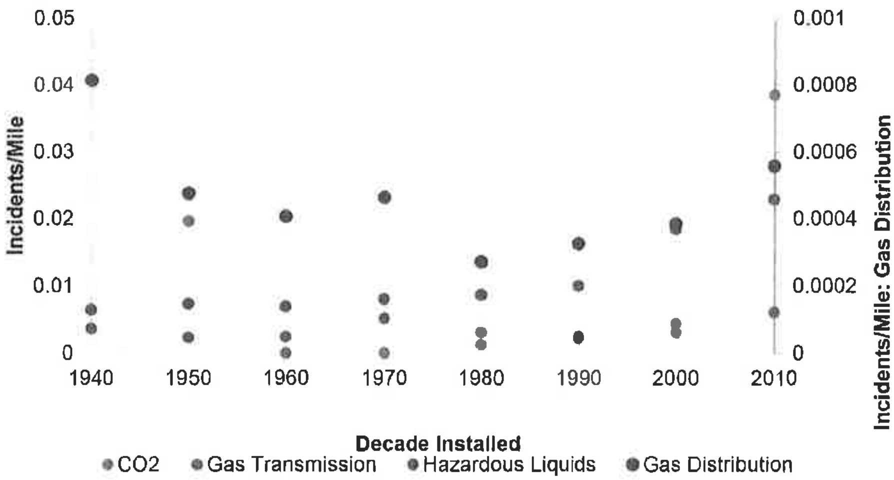

Fig. 4. Accident per mile by decade installed.

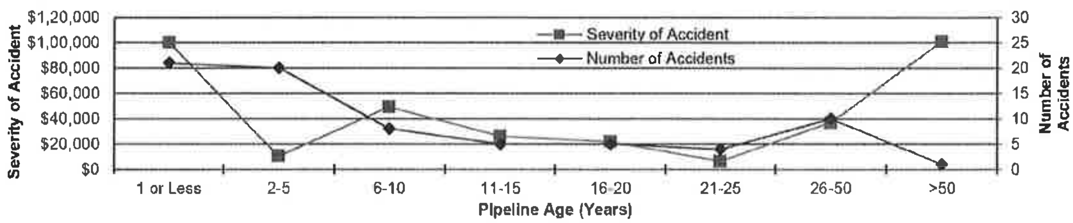

Fig. 5. Number and severity of CO_2 pipeline accidents, by age.

opposition. At this point, no NGO exists whose sole purpose is to stop the development of CCUS. There are, however, several publicized accidents in recent years where opposition to pipelines has been highly politicized, such as the Keystone XL Pipeline, which was routed from the Tar Sands in Alberta, Canada, to oil refineries in the southern United States, (Nicholson, 2017) and the Dakota Access Pipeline, which was routed in a sensitive area of the Missouri River sacred to the Sioux Tribe (Hersher, 2017). Both projects have faced opposition from native tribes of Canada and the United States. This factor, combined with the fact that the pipeline has the largest footprint of any of the components of the proposed CCUS project, makes it the activity most susceptible to public opposition. While the proposed project will not be transporting oil or other highly toxic liquids with the potential to pollute the environment, the construction process could be disruptive to sensitive areas. As a result, careful consideration of potential receptors and sensitive areas should be taken. In addition, residents concerned with safety issues for CO_2 pipelines should be educated about the safety of existing CO_2 pipelines. The risk values estimated in this study show that most of the risk posed by a CO_2 pipeline occurs during construction. This is an important point for project outreach because construction risks are unlikely to affect the general public. The operational risk posed by CO2 pipelines is small compared to other pipeline types. This information maybe be valuable to project outreach efforts addressing pipeline opposition.

6. Conclusions

Risks associated with CO_2 pipelines are significantly less than those of other pipeline types. The likelihood of an accident occurring at a CO_2 pipeline was higher than at a natural gas distribution or transmission pipeline (i.e., 10 accidents for 1000 miles of pipeline for CO_2 pipelines as opposed to 0.4 accident and 4 accidents per gas distribution and gas transmission pipelines, respectively). This may be the result of a lower threshold for reporting hazardous liquid pipeline accidents (including CO_2 pipelines) versus natural gas pipeline accidents. In addition, the consequences of the accidents at CO_2 pipelines were significantly less than those of any other pipeline type. For instance, while the other pipeline types had multiple accidents with fatalities, injuries requiring hospitalization, evacuations, ignitions, and explosions, accidents at CO_2 pipelines did not have any of these consequences. In addition, only one accident at CO_2 pipelines required remediation compared to accidents at non-CO_2 hazardous liquid pipelines, which led soil and water contamination, wildlife impact, remediation, or long-term assessment. Monetary costs related to CO_2 pipelines were orders of magnitude lower than those of other pipeline types, never exceeding around $205,645 compared to maximum costs of $734 million, $588 million, and $841 million for gas distribution, gas transmission, and non-CO_2 hazardous liquid pipelines, respectively. The data developed in this study are useful for project developers to estimate their risk exposure in dollars that can be used to buy insurance throughout the project. Furthermore, calculation of risk using money allows an easy way to describe risk to the public for outreach because people are generally familiar with money.

Author statement

This work was equal collaboration among authors

Supplemental material

Pipeline Supplemental Data.docx

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2022.103636.

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